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Effect of Protective Clothing and Fatigue on Functional Balance of Firefighters

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Abstract

We investigated the effects of wearing personal protective equipment (PPE), design of PPE (*Standard vs. Enhanced*), and fatigue during a simulated firefighting activity on the functional balance of firefighters. We defined functional balance as the ability to prevent a loss of balance and maintain body posture while performing functional tasks. A novel Functional Balance Test (FBT) was used to assess functional balance of firefighters while stepping up, stepping down, turning, walking along a beam, and passing under an obstacle. Data are presented from fifty-seven male firefighters, who were randomly divided into two groups: *Standard* PPE (n=28) and *Enhanced* PPE (n=29). The specially designed *Enhanced* PPE was lighter, more breathable, and capable of air circulation, compared to traditional *Standard* PPE. Each participant performed the FBT at three time periods (baseline with station uniform, pre-activity with PPE, and post-activity with PPE after a live-fire simulated firefighting activity). The firefighting activity involved alternating 2-minute rest- work cycles of four stations: stair climb, forcible entry, room search, and hose advancement. The FBT had four trials each with and without an overhead obstacle. Performance errors (major and minor), performance time, and a composite performance index were recorded. Wearing PPE significantly impaired functional balance, as noted by increases in all performance metrics. Following the firefighting activity, performance time increased by 3% but the number of minor and major errors decreased by 13% and 32%, respectively, suggesting that firefighters may trade-off between speed and accuracy depending on perceived threat to balance safety. There was no significant difference in functional balance between the *Enhanced* PPE and *Standard* PPE groups, suggesting that *Enhanced* PPE with a passive cooling system and an external circulating hose is not effective in improving functional balance of firefighters. A better designed PPE, with an improved cooling system and minimal (or no) protruding attachments may be of benefit in terms of firefighter functional balance.

Keywords: Firefighting; Personal protective equipment; Functional balance; Overhead obstacle

Introduction

Every year, more than 38,000 firefighters are injured on the fireground [1]. Among causes of moderate or severe injuries of firefighters, slips, trips, and falls are the most significant cause (28%) of firefighting injuries, followed by overexertion (23%), struck by objects (17%), exposure to detrimental environment (15%), and others (17%) [1]. A 2003 study reported that the average medical cost per claim due to slips, trips, and falls was $8,662 – a value that was 60% higher than the average costs for all claims [2]. Firefighters regularly work in hot, smoky, and slippery fireground conditions with many obstacles. To provide protection under these circumstances, firefighters wear fully encapsulating “bunker gear style” personal protective equipment (PPE), which includes bunker coat, bunker pants, boots, helmet, face mask, gloves, and self-contained breathing apparatus (SCBA) [3]. The primary design requirements for firefighting PPE are to provide protection from the by-products of combustion (heat, smoke, gases), but current designs and typical materials have significant negative impacts on balance, mobility, thermoregulation, etc. Furthermore, during emergency operations, firefighters may become fatigued by the strenuous firefighting activity and heat stress, which can further impair balance control.

In spite of the obvious benefits of PPE in protecting firefighters from heat, smoke and fire, the use of PPE may negatively affect firefighters’ functional balance. Functional balance was defined as the ability to prevent a loss of balance and maintain body posture while performing functional tasks. Wearing PPE may impair the functional balance of firefighters due to its heavy weight, bulkiness of the material, and a SCBA face mask, which limits vision [4,5]. Wearing PPE also changes the firefighter’s center of gravity [6], increases fatigue [7], and imposes physiological burdens, e.g., increased oxygen consumption and heart rate [7–10]. The heavy, insulative aspect of PPE also contributes to increased metabolic work done by the firefighter, resulting in increased heat stress [11,12] that might negatively impact functional balance. During firefighting activity, heat stress and the resulting elevation in body temperature hastens muscular fatigue, promotes dehydration, increases cardiovascular strain, and interferes with cognitive function [13,14]. While relatively few studies have investigated the effects of firefighting PPE on functional balance [4,15], no studies have been found related to the effects of fatigue due to firefighting activity on the functional balance of firefighters.

Modifying the design of current bunker gear style PPE (Figure 1a) to reduce the bulk, restrictiveness and thermal burden of the fully

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Figure 1: Two PPE configurations. (a) *Standard* PPE: helmet, heavily insulated hood, bunker style coat and pants, and rubber boots. (b) *Enhanced* PPE: lighter helmet, Nomex hood, bunker style coat and pants with reduced insulation and passive cooling system, and light weight leather/Kevlar boots.

encapsulating coat and pant has potential to improve the functional balance of firefighters. Researchers have found that reducing SCBA weight can enhance gait performance [6], and different PPE clothing configurations can reduce thermal and cardiovascular strain [11] and reduce time to complete firefighting tasks during live fire drills [12]. Reducing the weight of PPE and introducing an air circulation system to reduce heat stress may serve to improve the functional balance of firefighters.

A prototype PPE with relatively light-weight clothing and passive air circulation system within the coat was recently designed and developed (Total Fire Group (Dayton, OH) and International Personnel Protection Inc. (Austin, TX)) (Figure 1b). This PPE met the US guidelines (NFPA 1971) for thermal protection of structural firefighting clothing. However, it was not known whether this *Enhanced* PPE could improve functional balance of firefighters compared with *Standard* assigned PPE.

Current balance assessment tests may not be appropriate for fatigued firefighters who completed strenuous firefighting activities. Traditional postural sway assessments are frequently used to assess balance [4,16,17]. In such tests, the subject stands for a period of time (e.g., 30-60 seconds) on a force platform to record the movement of the center of pressure under the feet. Postural sway assessment was found to be infeasible for the current study because fatigued firefighters were unable to complete the necessary repeated trials of quiet standing in their PPE due to the accumulation of heat stress and subsequent venous pooling. During the design stage of the current study, several firefighters reported feeling faint while attempting this protocol. *Punakallio et al.* [4,16,18] developed a functional balance assessment test for non-fatigued firefighters during which the subject walked forward and backward along a wooden plank (2.5 m (L), 9 cm (W), and 5 cm (H)). The Punakallio test was judged to be too challenging and dangerous for our test subjects after a bout of strenuous activity due to the required backward walking on the narrow plank. Therefore, development of a revised functional balance assessment test was needed particularly when studying firefighters who had just completed a strenuous bout of firefighting activity.

Therefore, the objective of this study was to examine the effects of wearing of PPE, design of PPE, and strenuous firefighting activity on the functional balance of firefighters. Specifically, functional balance was assessed: 1) while wearing PPE (station blues vs. PPE), 2) while wearing different PPE designs (*Enhanced* vs. *Standard*), and 3) following a bout of strenuous live-fire firefighting activity. Furthermore, to assess functional balance, especially during a fatigued state, a novel functional balance test was developed.

Methods

Participants

Sixty-one male firefighters (ages 18-47 years) were recruited from the Illinois Fire Service Institute (IFSI) training events and local fire companies. All participants reported no neurological or postural disorders. Females were not recruited in this cohort as the work presented in this paper was part of a larger study that included cardiovascular outcomes, many of which are strongly affected by the female menstrual cycle [19]. In addition, the majority of firefighters in the United States are men. Informed consent was given by all participants and the study was approved by the Institutional Review Board at the University of Illinois. Participants were divided into two groups: 1) control group with *Standard* PPE (n=31), and 2) intervention group with *Enhanced* PPE (n=30). Data from four participants were excluded from the data analysis since they were not able to complete the post-activity evaluation due to physical fatigue after the simulated firefighting activity. The final sample included 57 participants (control, n=28; intervention, n=29). Participants' age, height, mass, body mass index (BMI), and months of firefighting experience were collected.

Standard/Enhanced PPE

The control group wore a *Standard* PPE ensemble similar to that currently used by firefighters in the United States. This PPE included 1) a traditional style helmet, 2) insulated hood, 3) bunker style coat and pants with relatively heavy insulation and low breathability, and 4) rubber boots**.** 1a) On average, the full set of *Standard* PPE (excluding SCBA mass) weighed 11.1 kg. The intervention group wore an *Enhanced* PPE ensemble designed with industrial partners of IFSI (Total Fire Group (Dayton, OH) and International Personnel Protection Inc. (Austin, TX)) that included: 1) a lighter, low profile helmet, 2) more breathable Nomax hood, 3) bunker style coat and pants with materials that provide reduced insulation, improved breathability, and a passive cooling system to assist with heat transfer in the coat; and 4) lightweight leather/Kevlar .1b) The novel passive cooling system was intended to circulate exhaled air from the firefighter's face piece to the coat's inner lining. The microclimate inside fully encapsulating PPE rapidly becomes fully saturated with moisture due to heavy sweat production during firefighting activities, resulting in uncompensable heat stress. It was hypothesized (though not tested prior to this study) that the moist air circulated from the breath would have lower relative moisture than the air within the PPE. The goal was to create air movement inside the PPE to assist with heat dissipation and reduce the relative humidity by pushing out the fully saturated, warmer air and thereby provide a means for evaporative cooling within a fully encapsulating PPE design. On average, the full set of *Enhanced* PPE (excluding SCBA) weighed 9.5 kg. Both PPE ensembles met current NFPA 1971 *Standard*s for thermal protection and breathability. Both groups wore identical SCBA packs (50i SCBA, Scott) with a 4500 psi 30-minute carbon fiber bottle (DOT # E10951-4500, Luxfer). The SCBA packs with a carbon fiber bottle were an additional 9.5 kg.

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Functional Balance Test (FBT)

In this study, a functional balance test (FBT) was developed to assess the functional balance of firefighters in a manner that could be safely conducted after completing strenuous firefighting activities. The FBT was designed to be a more tractable and applicable functional balance test than that proposed by *Punakallio et al.* [4,16,18], as it could be safely utilized while in a fatigued state and included additional tasks that might be encountered on the firegrounds. The test included stepping up and down from a platform, walking along a narrow walkway, and ducking under an overhead obstacle. Specifically, the FBT involved walking from one raised platform (15 cm (H)), stepping down and walking along a narrow plank (3m (L), 15 cm (W), 4 cm (H)), stepping up and turning around within a small defined space (61×61 cm^2) on a second raised platform (10 cm (H)), and walking back to stop within a defined space (61×61 cm^2) on the original platform (Figure 2a). The small defined space represented the need to stop or turn within a confined space, but with larger actual surface area for safety of the test subject. The task was made more challenging during some trials (see below) by placing an overhead obstacle (a lightweight wooden rod) across the center of the pathway at 75% of the participant's height (Figure 2b). The rod was supported by vertical supports placed approximately 114 cm apart. The obstacle was included to mimic the need to pass through a low confined enclosure without hitting the structure. For safety, the rod was designed to fall away if the rod or supports were hit, rather than being a rigid structure. For each testing period, participants performed eight trials: two trials with no obstacle, four with the obstacle, and finally two with no obstacle trials (same as the first two trials). Participants were instructed to perform the task as quickly and safely as possible without committing errors (see below for the definition of errors). Each trial was timed by two investigators and the averaged time of these measurements was used.

The number of errors that each participant made was recorded. A minor error was counted when: 1) a foot or hand contacted the ground, 2) a hand contacted a platform, 3) the turn was not completed within the defined space in the platform, 4) the participant could not stop within the defined space, or 5) the obstacle was touched but did not fall. A major error was counted when the obstacle was contacted and the rod fell. This event was considered to be a major error because had the firefighter hit a rigid obstacle then the impact could have caused a potentially dangerous and destabilizing effect on balance.

Participants were instructed that their score would be penalized if they committed any of the above errors. If an error was committed, the investigator informed the participant of the error and advised him to try to not repeat the error during the subsequent trials.

Experimental protocol

To assess the effects of wearing PPE, wearing different designs of PPE, and strenuous firefighting activity on functional balance, participants were evaluated at three testing periods: baseline (BL) with station blues (typically t-shirts and jeans), pre-activity (PRE) with PPE on before firefighting activity, and post-activity (POST) with PPE on after firefighting activity.

The firefighting activity was designed to simulate realistic firefighting scenarios and developed in consultation with Firefighting Program staff members at IFSI. The activity consisted of 18-minutes of alternating rest-work cycles. These cycles included four stations: stair climb, forcible entry, room search, and hose advancement (Figure 3). The firefighting activity took place on the second floor of a live-fire training building, where a contained live fire was stoked in a portion of the room. To create a near-realistic fireground scenario, the room had no external or artificial lighting and temperatures at waist level (1.2 m above the ground) averaged between 71-82°C. Humidity was not controlled during these scenarios, but was expected to be very low due to the significant radiant heat load in the room and ample ventilation allowing the buoyant driven flows to release all evaporated moisture to the air. Each station took 2 minutes and was followed by a 2-minute rest break. Prior to starting the first station, the participant rested in the training building for 2 minutes to acclimate to the high temperature environment. For each testing period (i.e., BL, PRE and POST), the FBT was performed on the first floor of the training building. The FBT for POST occurred within 1-2 minutes after completing the simulated firefighting activity. The effect of wearing PPE was examined by comparing BL and PRE. The effects of PPE design and strenuous firefighting activity were examined by comparing PRE and POST.

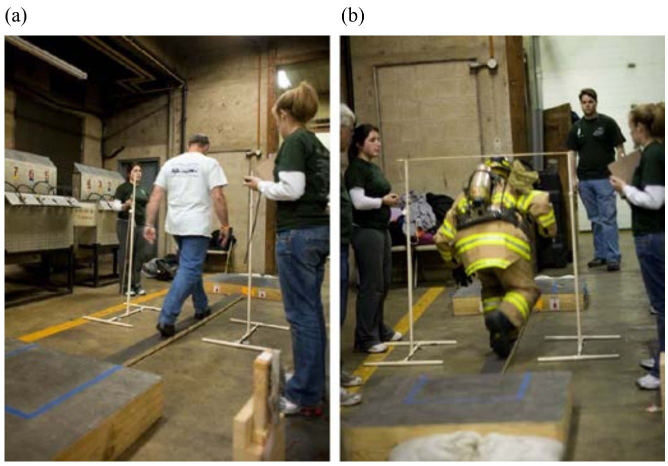

Figure 2: Functional balance test. (a) Baseline condition in station blues with no obstacle trial. (b) Trial with obstacle while wearing PPE.

Figure 3: (a) Environment for simulated firefighting activity involved a live fire stoked in a portion of the testing room. Simulated firefighting stations (2 minutes each): (b) stair climb, (c) forcible entry, (d) room search, and (e) hose advancement. All participants had 2 minute breaks before and after each station.

To assess any association between PPE design and strenuous firefighting activity and physiological data, heart rate and core temperature were recorded for both PPE designs at PRE and POST. Participants ingested a silicone-coated gastrointestinal (GI) core temperature capsule (Mini Mitter, VitalSense; Philips Respironics, Bend, OR) six to 12 hours prior to reporting for the study. Participants were instrumented with a heart rate monitor (Polar Electro Oy, Kempele, Finland). Physiological data were only available for 27 subjects in each PPE design group due to technical issues.

Data analysis

The number of major errors, minor errors, and performance time were recorded by four independent research staff members, two measuring errors and two operating stopwatches. Similar to *Punakallio et al.* [4,16,18], a performance index was created from the weighted sum of major and minor errors and performance time (Eq. 1). Greater weight was put on major errors than minor errors since a major error was considered a critical error on the fireground. Specifically, weighting factors for performance time and minor errors were set to one as in *Punakallio et al.* [4,16,18], whereas a weighting factor for a major error was set to two (Eq. 1).

$$\text{Performance Index} = 2\times\text{MajorError} + 1 \times \text{Minor Error} + 1 \times \text{Performance Time} \quad (1)$$

A three-way repeated measures multivariate analysis of variance (MANOVA) was performed to examine the effects of PPE ensemble design (*Standard* vs. *Enhanced*), existence of obstacle (without vs. with), and testing period (BL, PRE, and POST) on the four FBT variables (number of major errors, number of minor errors, performance time, and performance index). The within-group factors were the existence of an obstacle and the testing period. The between-group factor was design of PPE. Once significant effects were found in the multivariate analysis, subsequent univariate repeated measures ANOVAs were used to examine significant effects. Post hoc tests to identify significant main or interactions effects used the LSD approach (Fisher's least significant difference). A two-way repeated measures MANOVA was also performed to examine the effect of PPE ensemble (*Standard* vs. *Enhanced*) and firefighting activity (PRE vs. POST) on heart rate and core temperature. The level of significance was set to $\alpha=0.05$. Statistical analyses were run on SPSS (SPSS Inc., Chicago, IL; v17).

Results

There were no significant differences between the *Standard* and *Enhanced* PPE ensemble groups for any demographic values (Table 1).

	***Standard* PPE** (n=28)	***Enhanced* PPE** (n=29)	***p*-value**
Age (years)	26.4 ± 6.5	28.2 ± 6.5	0.32
Height (m)	1.78 ± 0.07	1.79 ± 0.06	0.82
Weight (kg)	84.6 ± 13.7	87.9 ± 13.1	0.23
BMI (kg/m^2)	26.6 ± 3.5	28.1 ± 4.0	0.12
Experience (months)	69.8 ± 69.6	68.8 ± 83.3	0.96

Table 1: Demographics of two PPE groups (Mean ± SD).

The overall behaviors of functional balance are shown in Figure 4 as functions of testing period (which can be further parsed as wearing PPE (BL vs. PRE) and firefighting activity (PRE vs. POST)), design of PPE (*Standard* vs. *Enhanced*), and obstacle presence (Obstacle vs. No Obstacle). The MANOVA revealed significant main effects for obstacle presence and testing period ($p<0.001$), but not design of PPE ($p=0.2$). Thus there was no significant difference in performance on the FBT as a consequence of design of PPE used.

The MANOVA also detected a significant two-way interaction for testing period and obstacle presence ($p<0.001$). Subsequent univariate repeated measures ANOVAs revealed that the presence of an obstacle significantly increased number of major errors (0.80 ± 0.08 (with obstacle) vs. 0.00 ± 0.00 (without obstacle), mean ± SE, $p<0.001$), minor errors (0.81 ± 0.11 vs. 0.38 ± 0.06, $p<0.001$), performance time (6.50 ± 0.12 s vs. 6.04 ± 0.10 s, $p<0.001$), and performance index (8.9 ± 0.3 vs. 6.4 ± 0.1, $p<0.001$).

The ANOVAs also revealed that testing period significantly affected number of major errors ($p<0.001$), minor errors ($p=0.012$), performance time ($p<0.001$), and performance index ($p<0.001$). Post hoc tests showed that wearing PPE (BL vs. PRE) significantly increased major errors (0.02 ± 0.01 vs. 0.70 ± 0.08), minor errors (0.40 ± 0.06 vs. 0.74 ± 0.12), performance time (5.73 ± 0.10 s vs. 6.45 ± 0.12 s), and performance index (6.2 ± 0.1 vs. 8.6 ± 0.3) ($p<0.05$). Firefighting activity (PRE vs. POST) significantly decreased major errors (0.70 ± 0.08 vs. 0.48 ± 0.07) and significantly increased performance time (6.45 ± 0.12 s vs. 6.65 ± 0.13 s) ($p<0.05$), but did not affect minor errors (0.74 ± 0.12 vs. 0.65 ± 0.12) and performance index (8.6 ± 0.3 vs. 8.3 ± 0.2) ($p>0.05$). All of the four FBT values also increased significantly between BL and POST ($p<0.05$). These results suggest that wearing PPE and/or firefighting activity significantly reduce functional balance (Figure 4).

Significant two-way interactions between testing period and obstacle presence were found for all four FBT variables: minor error ($p=0.046$); major error, performance time, and performance index ($p<0.001$) (Figure 4). These results highlight that the addition of PPE (BL compared to PRE or POST) caused a reduction in functional balance, which escalated with the presences of the overhead obstacle.

Firefighting activity significantly increased heart rate (95.6 ± 2.5 beat/min (PRE) vs. 170.3 ± 1.7 beat/min (POST), $p<0.001$) and core temperature (37.6 ± 0.1 °C vs. 38.4 ± 0.1°C, $p<0.001$) (Figure 5). However, design of PPE did not affect heart rate and core temperature ($p>0.05$). There was no interaction effect between firefighting activity and design of PPE on these physiological variables ($p>0.05$).

Discussion

The purpose of this study was to investigate the effects of PPE and fatigue due to strenuous firefighting activity on the functional balance of firefighters with a newly- developed functional balance test. It was hypothesized that wearing PPE (PRE) and strenuous firefighting activity (POST) would negatively affect functional balance compared to BL. It was further hypothesized that *Enhanced* PPE would improve the functional balance of the firefighters compared to *Standard* PPE.

We found that, regardless of PPE design, wearing PPE significantly impaired all four measures of functional balance (i.e., minor error, major error, performance time, and performance index) (Figure 4). Specifically, firefighters slowed down their movement speed when they wore PPE as evidenced by 13% increase of performance time for PRE compared to BL. Even with reduced movement speed, firefighters made significantly more errors when they were wearing PPE compared to BL. These findings extend prior research [4,7,15] which found that the weight of PPE is an important factor that impedes the functional balance of firefighters. Furthermore, we found that wearing PPE could be even more detrimental for functional balance when an overhead obstacle was present. A significant interaction between obstacle presence and testing period suggests that presence of the overhead

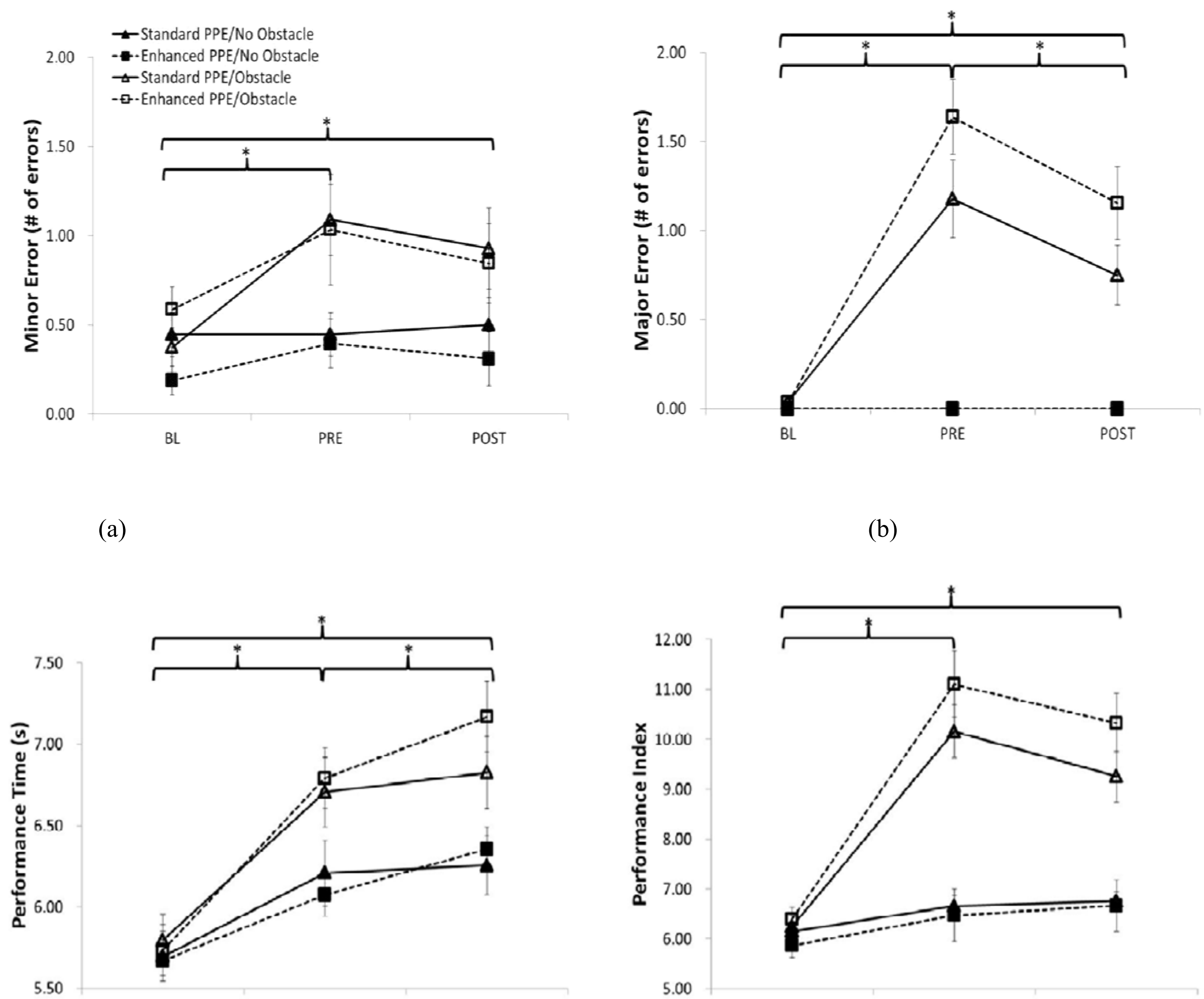

Figure 4: Plots of (a) Minor Errors, (b) Major Errors, (c) Performance Time, and (d) Performance Index during the FBT as functions of design of PPE, obstacle conditions, and testing period. Error bars represent standard error. Significant main effects for testing period pairings are indicated with an asterisk symbol (*).

obstacle further accentuated the negative impact of wearing PPE on functional balance (Figure 4). Therefore, wearing PPE can threaten functional balance of firefighters on the fireground.

Strenuous firefighting activity was found to significantly impair functional balance. After a bout of strenuous live-fire firefighting activity (POST), firefighters reduced their movement speed (3% increased performance time) compared to PRE condition (Figure 4c). Interestingly, the number of major errors also decreased significantly (by 32%) for POST compared to PRE condition (Figure 4b). As a result of the reduction in major errors, the performance index was not affected by strenuous firefighting activity (Figure 4d). These findings suggest that firefighters were proceeding with greater caution following a strenuous bout of firefighting activity. The reduction of errors appears not to be due to a learning effect since the number of minor errors in the first two trials was not significantly different from the number of minor errors in the last two trials ($p>0.05$). Rather, it is possible that firefighters used a trade-off strategy to compromise between speed and accuracy. The instruction given to firefighters was to complete the task as safely and quickly as possible. According to *Chambers and Cham* [20], healthy young adults who experienced a slip adapted their gait strategy proactively with larger muscle activity, larger muscle co-contraction, earlier muscle onset and longer muscle activation compared to baseline condition, which can help reduce severity of slip. *Cham and Redfern* [21] reported that expectation of a potentially slippery surface can lead to a more "cautious" gait strategy in healthy young adults. Therefore, we speculate that after the firefighting activity, firefighters changed their movement strategy, proactively adjusting their own weighting factors for speed and accuracy for a given condition (PRE vs. POST). Before the strenuous firefighting activity, firefighters could have put more weight on speed over accuracy. After the firefighting activity, firefighters became more careful and put more weight on accuracy over speed. According to *Del Percio et al.* [22], fatigue did not affect visuo-spatial attention of elite karate athletes. Similarly, it can be speculated that even though muscle fatigue might have some influence on the

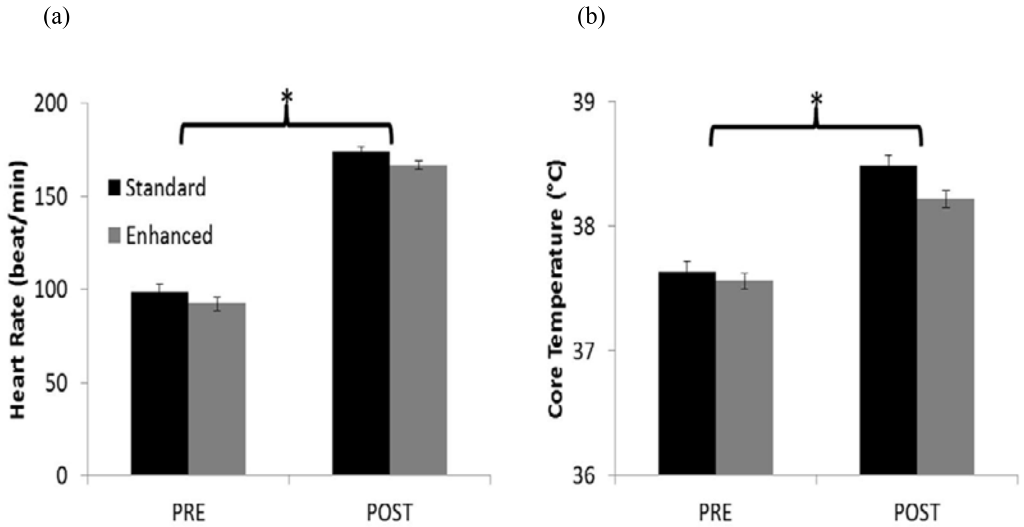

Figure 5: Plots of (a) heart rate and (b) core temperature as functions of design of PPE and testing period. Error bars represent standard error. Significant main effect for firefighting activity is indicated with asterisk symbol (*).

functional balance of firefighters, muscle fatigue did not affect visuo-spatial attention of the firefighters. This argument is reasonable because firefighters are trained to be cautious and avoid running unless it is an urgent and life-threatening situation, despite the fast paced and often chaotic fireground environment.

It was also hypothesized that *Enhanced* PPE would improve the functional balance of the firefighters compared to *Standard* PPE. However, the *Enhanced* PPE, which was lighter, more breathable, and capable of air circulation, did not improve the functional balance of firefighters. Contrary to the hypothesis, the *Enhanced* PPE group tended to have a higher performance index value (by 8%) compared to *Standard* PPE when considering the obstacle condition (Figure 4d, p=0.2). This negative trend in performance index was driven by the tendency to have more major errors while wearing the *Enhanced* PPE (Figure 4b) and longer performance time (Figure 4c) for POST. Furthermore, we did not find any difference in the average core temperature or heart rate of the firefighters wearing *Standard* vs. *Enhanced* PPE, thus the intervention was not successful in reducing the heat stress or physiological strain of the firefighting activity. One reason for these outcomes may be that the firefighters were not accustomed to the novel *Enhanced* PPE. The *Enhanced* bunker coat and pants were custom-made and available to firefighters for the first time during the experiment. Even though the PPE was lighter and less restrictive, a number of firefighters found the protruding circulation hose on the coat to be cumbersome and in some instances it was this aspect of the PPE that hit the obstacle when firefighters passed under. *Enhanced* PPE may have not positively affected functional balance, but may help enhance other aspects of performance (e.g., range of motion). Firefighters in the *Enhanced* PPE group anecdotally reported that their range of motion increased compared to when they would wear their department-issued PPE.

The intent of the cooling system adopted in the *Enhanced* PPE design was to circulate exhaled air from the firefighter's face piece to the coat's inner lining so that the created air movement inside the PPE may assist with heat dissipation by providing a means for evaporative cooling within the fully encapsulating PPE. However, due to the relatively high moisture content and low velocity of the exhaled air, this approach did not provide a significant impact on functional cooling during the firefighting activity. It is possible that such a cooling system maybe improved through additional testing in a controlled laboratory using a sweating mannequin. An active cooling system may be more helpful reducing core temperature and heat stress of firefighters. *Selkirk et al.* [23] showed that, immediately after firefighting activity during a rehabilitation period, an active cooling system using forearm submersion significantly reduced core temperature and heart rate compared to a passive cooling system. They further showed that the active cooling group could work for a significantly longer time than the passive cooling group during subsequent work bouts after a cooling rehabilitation period. Therefore, an active cooling system administered immediately after firefighting during the rehabilitation period may have a greater impact on mitigating the post-firefighting declines in functional balance. For future PPE design, any additional external attachment such as the circulating hose employed in the *Enhanced* PPE in the present study, should be carefully examined for impact on functional balance and should not reduce the flexibility of the PPE.

Conclusions

It was found that wearing PPE significantly impaired functional balance by slowing down movement speed and increasing errors. This impairment was further escalated when an overhead obstacle was present. Strenuous firefighting activity resulted in slower performance speed and decreased number of errors, suggesting that firefighters may elect to trade-off speed for accuracy depending on the self-determined need for greater caution.

The prototype *Enhanced* PPE with a passive cooling system and an external circulating hose was found not to be effective in mitigating the rise in core temperature during firefighting activities or enhancing functional balance of firefighters. A better designed PPE, with an improved cooling system and minimal (or no) protruding hoses or attachments, may lessen heat stress and fatigue and may be of benefit in terms of firefighter functional balance.

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